The following illustrations are intended to bridge this gap and to show how coal resources data are utilized to construct bed maps. Many more illustrations could be prepared, but the accompanying figures are believed to be representative.

Figure 9 illustrates how to determine areas of reliability (areas based on distance of from points of thickness measurements—measured, indicated, inferred, and hypothetical coal) where a coal bed has been mapped on the surface and the thickness of coal has been measured

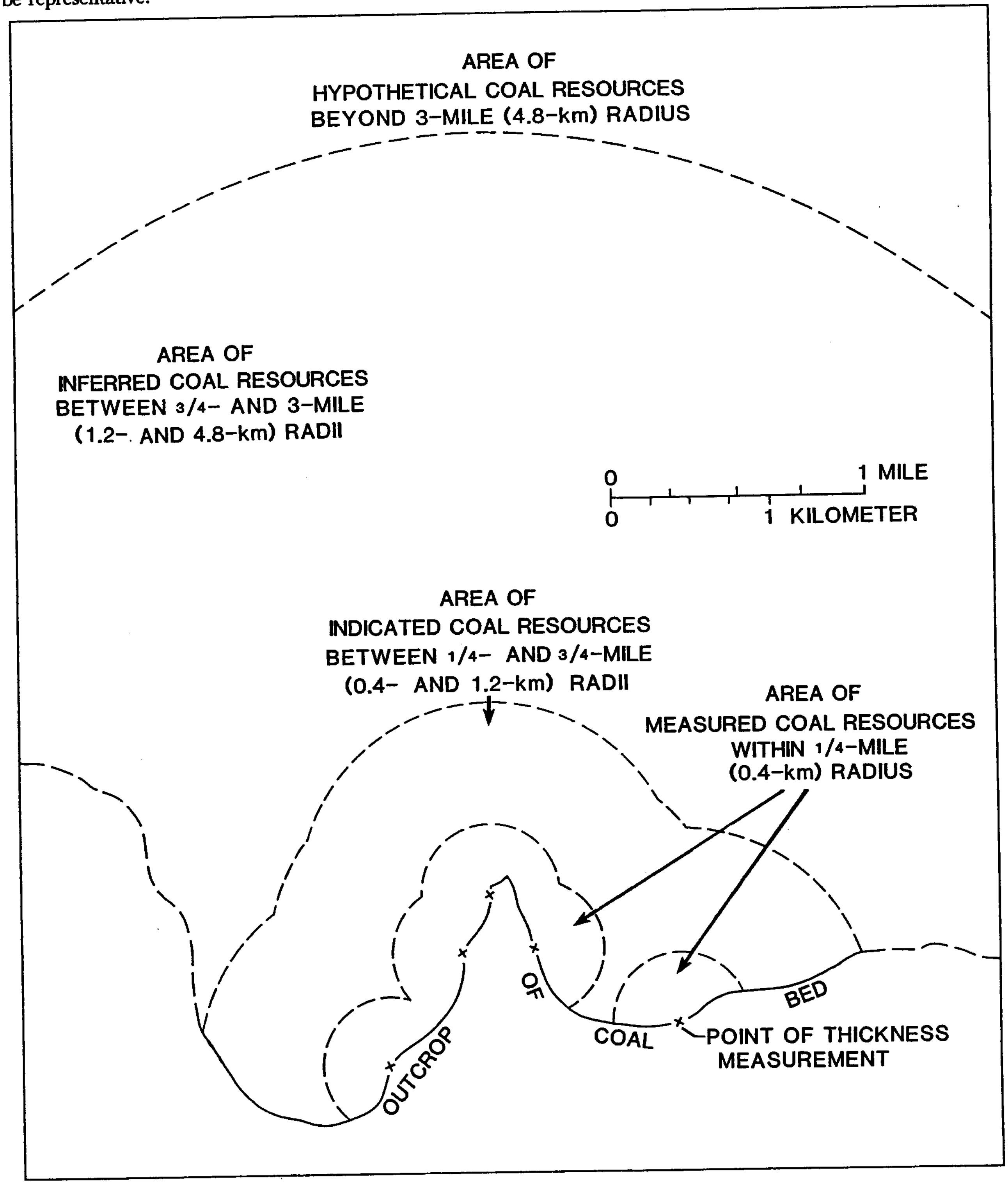

FIGURE 9.—Determination of areas of reliability using coal thickness data only at points of measurement along outcrop line. Radii origins are at points of thickness measurement.

Stagg Dec. -- Exhibit 2
APP. III 674

at five points. The solid outcrop line indicates where the bed has been mapped with assurance as to its intersection with the ground surface; the dashed line indicates uncertainty as to the exact location. Utilizing radii originating at the points of thickness measurements, arcs are constructed at appropriate distances according to the criteria for the measured, indicated, inferred, and hypothetical reliability categories. The arcs enclose areas theoretically underlain by coal for each reliability category.

Figure 10 uses the same coal bed outcrop as figure 9 and shows the effect of additional thickness information from drill-hole measurements and a small mine. A comparison of figures 9 and 10 illustrates how the additional data derived from drill-holes and mining expand the areas designated in figure 10 as measured and indicated and modify the inferred and hypothetical areas.

The objective of figure 11 is to show how drill-hole data combined with outcrop data on a continuously exposed strip-mined coal bed result in the coalescing of measured and indicated coal and in an expansion of the area of the inferred reliability category. It also shows how a single point of thickness of coal measurement defines an area of measured, indicated, and inferred coal.

The primary objective of figure 12 is to show how to construct a minimum thickness-of-coal isopach (14 inches) based solely on outcrop data. A secondary objective is to illustrate how to locate a coal outcrop and boundaries such as county lines on a bed map from a geologic map. Generally, as a bed thins along an outcrop, it is increasingly more difficult to trace. Figure 12 illustrates a simple, nearly straight coal bed outcrop with three thickness-of-coal measurements. The three measurements are all thicker than the 14-inch minimum thickness of coal considered when calculating anthracite and bituminous coal resources. The thickness gradients between the 26-inch and each of the 20-inch points of measurement of coal are extrapolated along the crop line to the east and west of the 20-inch measurements to points *A* and *B* where the coal gradients predict coal thicknesses of 14 inches. A straight line is then drawn between the predicted 14-inch points *A* and *B* on the crop line and subsequently is bisected at mid-point *O*. An arc *AB* is drawn between the predicted 14-inch points using either *AO* or *BO* as a radius. The arc *AB* locates the 14-inch isopach according to the available data on thickness and length of outcrop.

Figure 13 displays areas of reliability, thickness-of-overburden contours, political subdivisions, and a completed coal bed map ready for determinations of acreages and weighted average thickness of coal in each area. Areas *A* to *P* are ready for planimetry of acreages, for calculation of coal tonnages after weighted average thickness of coal for the areas are determined, and for subsequent entry on tonnage tables according to their assignment to a thickness of coal, thickness of overburden, reliability category, and to a county. Table 4 lists the areas of reliability by thickness of overburden category, by a single thickness of coal category, and by counties. To avoid confusion, figure 13 and table 4 were constructed with only one thickness of coal category, 14 to 28 inches. Subsequent figures are more complicated because more thickness categories are introduced.

Figures 14 and 15 show a diagram of a ridge underlain by coal; they also show the geometric method of determining the 14-inch minimum thickness of bituminous coal isopach and the areas of reliability constructed from the points of thickness of coal measurement. The 28- and 42-inch coal isopach lines were constructed by using the gradients between the various thicknesses of coal measurements. This method of determining the area of coal under a ridge is commonly necessary when thickness measurements are sparse and an estimation of coal resources beneath a ridge is required. Table 5 enumerates the areas assigned to the varous thicknesses of coal and overburden and reliability categories.

Figures 16 and 17 and table 6 show how to construct the 14-inch minimum thickness limit of anthracite or bituminous coal resources, other coal isopachs, and the areas of reliability and overburden isopachs for a simple valley reentrant in a coal bed outcrop. Figures 16 and 17 and table 6 are important because they show how to treat a valley reentrant in a coal outcrop characterized by minimal thickness data.

Figures 18 and 19 and table 7 show how to determine the location of the minimum coal isopach (14 inches for bituminous coal) in a valley and ridge underlain by a coal bed that is locally less than the minimum thickness. Figure 19 also illustrates the areas of reliability, overburden categories, and coal isopachs. The location of the minimum coal isopach (14 inches) on a ridge which has thickness data on only one side is a common problem facing geologists estimating coal resources.

One of the most difficult problems in estimating resources of coal is where the beds are moderately to steeply dipping or are highly deformed. A simplified problem is illustrated in figures 20*A*, *B*, and *C* by a bed that dips uniformly 30° into the subsurface. The problem as illustrated can be solved by two methods. The first method is to estimate all areal resource tonnages in the plane of the coal bed and then to project all pertinent areal categories to the ground surface. For example, the measured, indicated, inferred, and hypothetical reliability circles, coal isopachs, overburden contours,

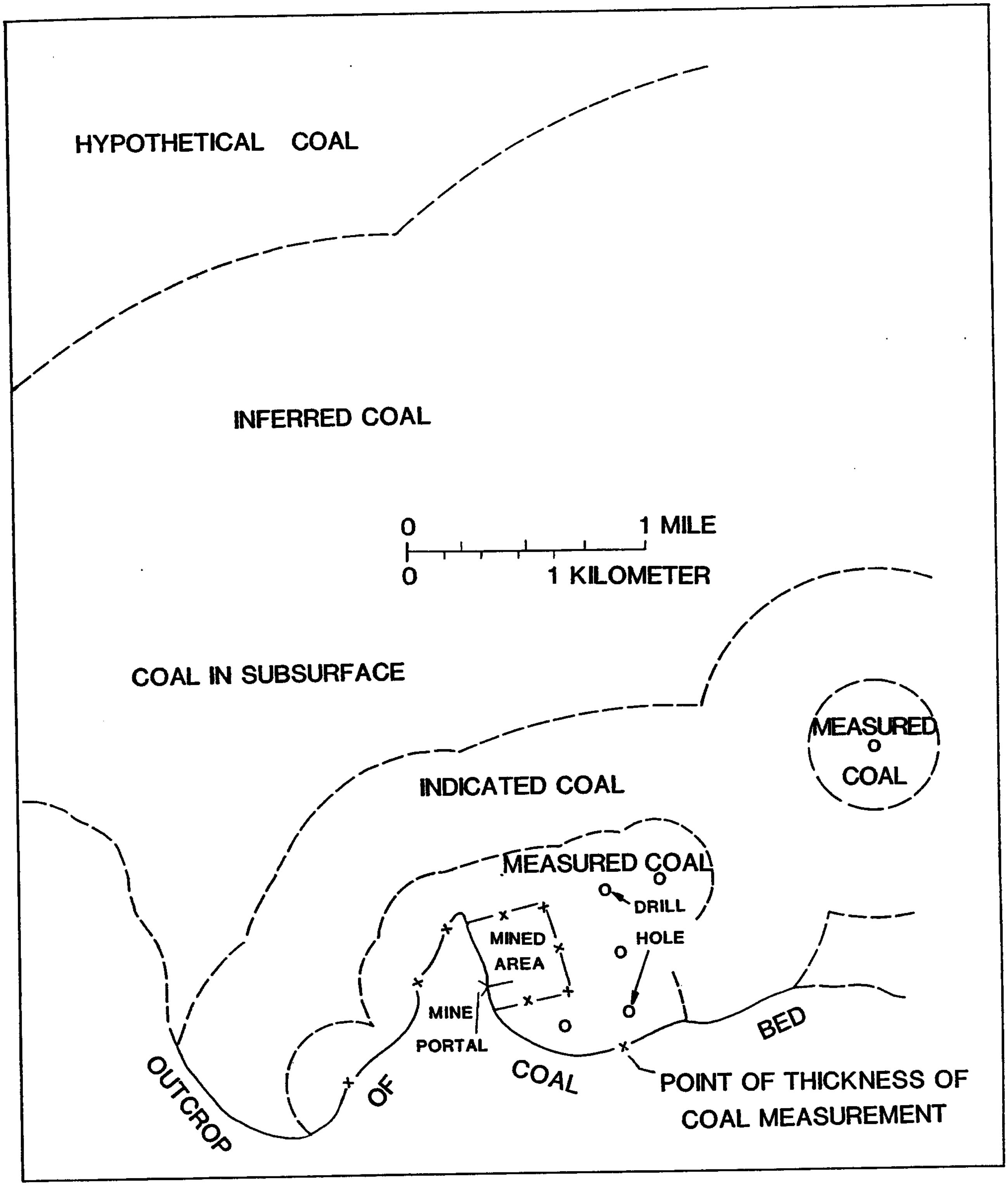

FIGURE 10.—Determination of areas of reliability from points of measurement on the outcrop line, supplemented by mine and drill-hole data.

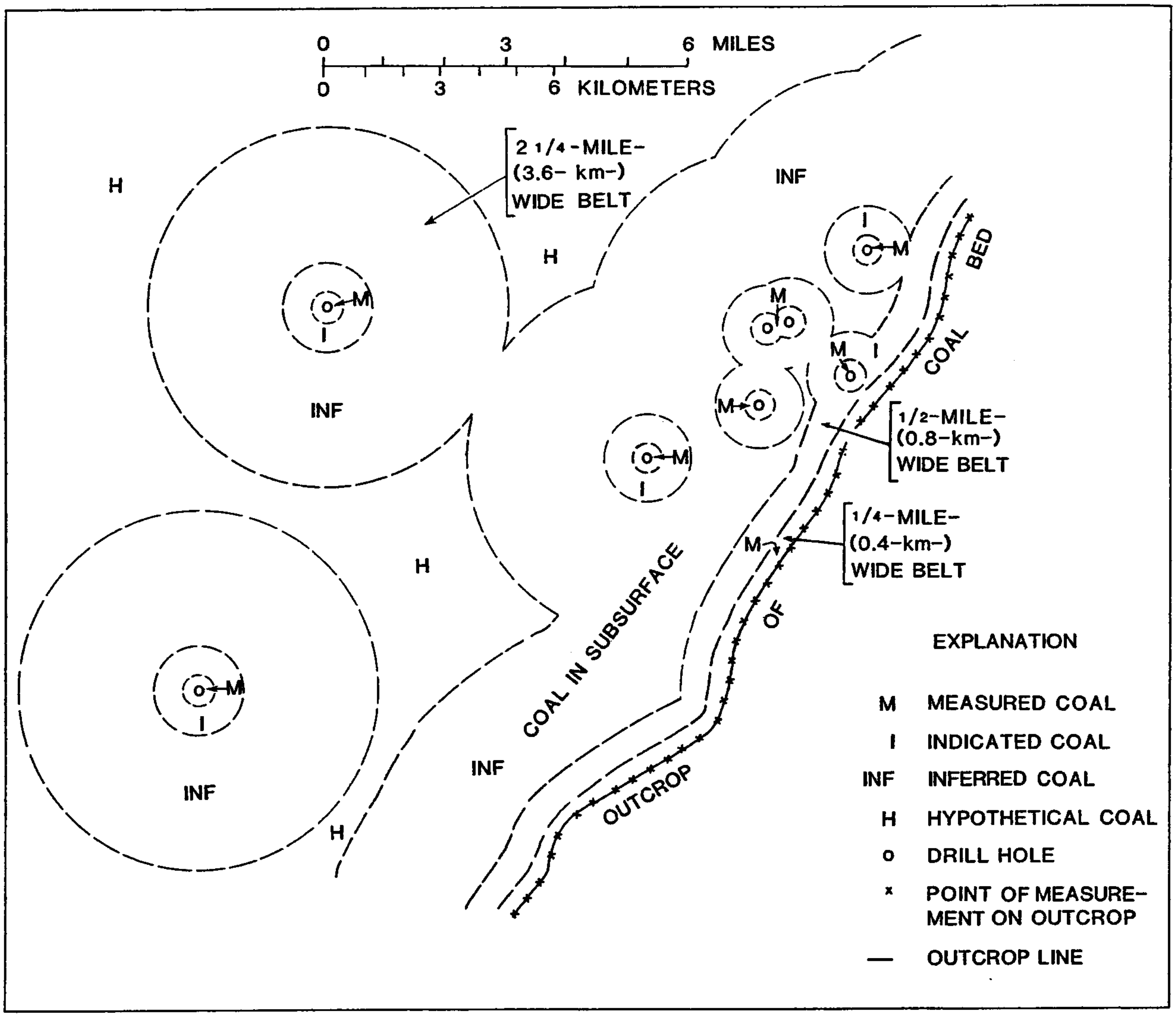

FIGURE 11.—Determination of areas of reliability using coal thickness measurements taken along a continuously exposed, strip-mined bed, supplemented by drill-hole data.

and structure contours should be drawn in the plane of the coal bed (fig. 20*A*). Then the areas of each of these categories are planimetered and coal tonnages estimated. This procedure provides an adequate estimate of coal tonnages for all values of dip. However, it is difficult to project the areas from the plane of the coal bed to the surface area overlying any particular category (fig. 20*B*). Although this method gives an adequate tonnage estimate, it distorts the ground surface depiction of areal categories (fig. 20*C*).

The second method is to draw the areal boundaries of the various categories on a surface map, measure the areas underlain by the various categories, and estimate the coal tonnages for each category. After estimation of the resources as if they were flat-lying, the estimates are divided by the cosine of the dip. The resultant answer is the tonnage in the plane of the bed. This method will provide correct tonnage estimates in each resource category underlying the surface but will horizontally exaggerate the areas of measured, indicated, and inferred coal and should be used only where the dip is more than 10° and less than 30°. For dips above 30°, it is recommended that resource estimates be made by the first method. For dips less than 10°, all estimation of resources should be done as if the bed was flat-lying.

The authors suggest that geologists involved with estimating the coal resources of highly deformed areas consult with coal geologists who have worked on similar areas and estimation problems. Currently, resource problems in highly deformed areas have not been solved

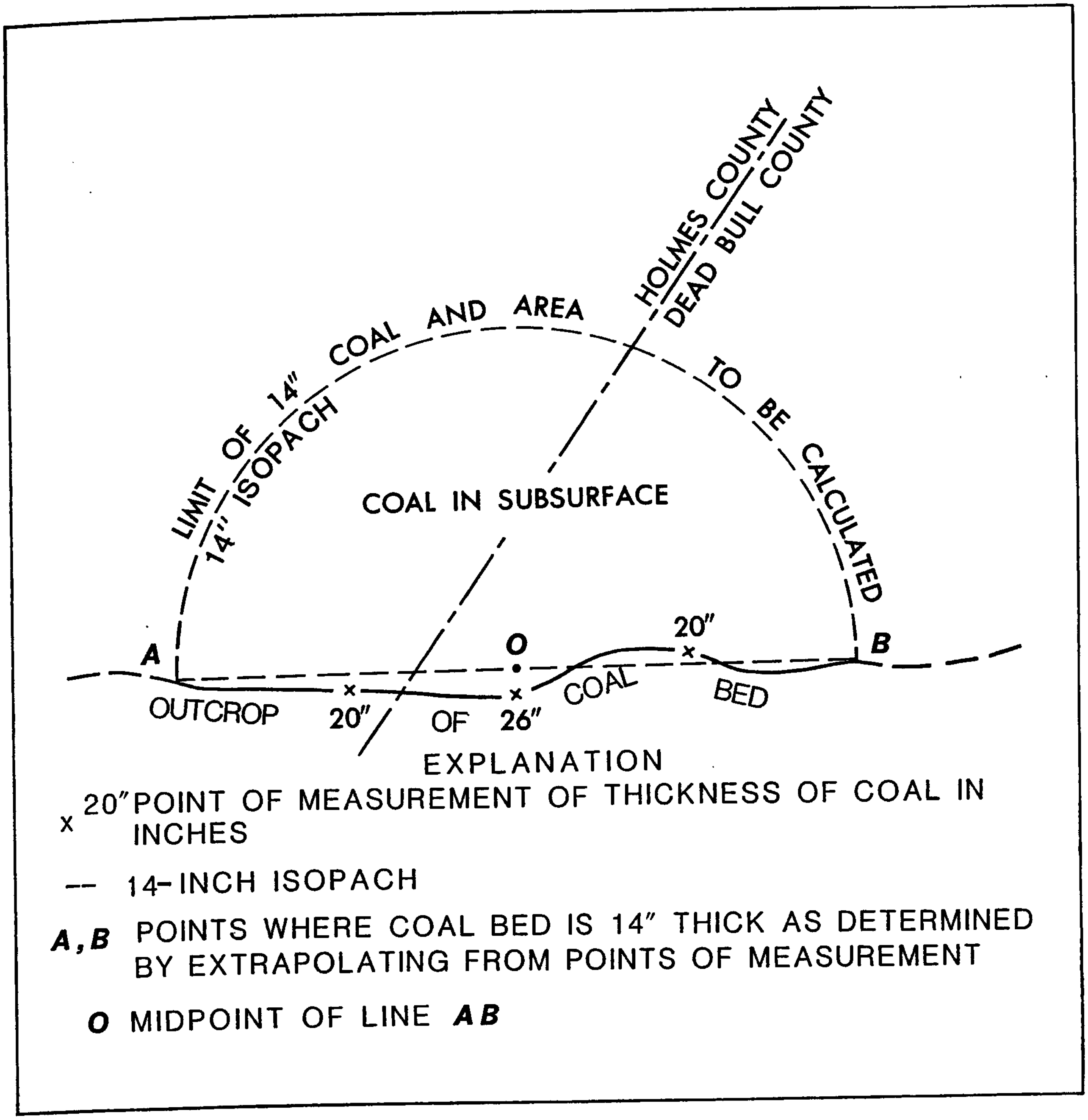

FIGURE 12.—Determination of minimum thickness isoline of 14-inch thick anthracite or bituminous coal using data from a nearly straight outcrop line. *A* and *B* are located on the outcrop line where the coal thickness as extrapolated from the points of measurement are predicted to be 14 inches. Line *AB* connecting the points of predicted 14-inch coal is bisected at *O*. The radius *AO* or *BO* is then used to construct arc *AB*, the 14-inch isopach or predicted limit of 14-inch-thick coal. This figure also shows the location of the outcrop line and a county boundary on a coal bed map as derived from a geologic map.

except locally for small areas. Although methods have been developed, they are generally very time consuming and as yet unproven by mining.

Figure 21 illustrates a coal bed that has been mined from shafts at some distance from outcrops. All data are derived from the mines or drill holes. The figure shows measured, indicated, inferred, and hypothetical coal; county lines; thickness of coal measurements; coal thickness categories; and the 0–200 feet, 200–300 feet, and the 300–500 feet overburden categories. It also shows a

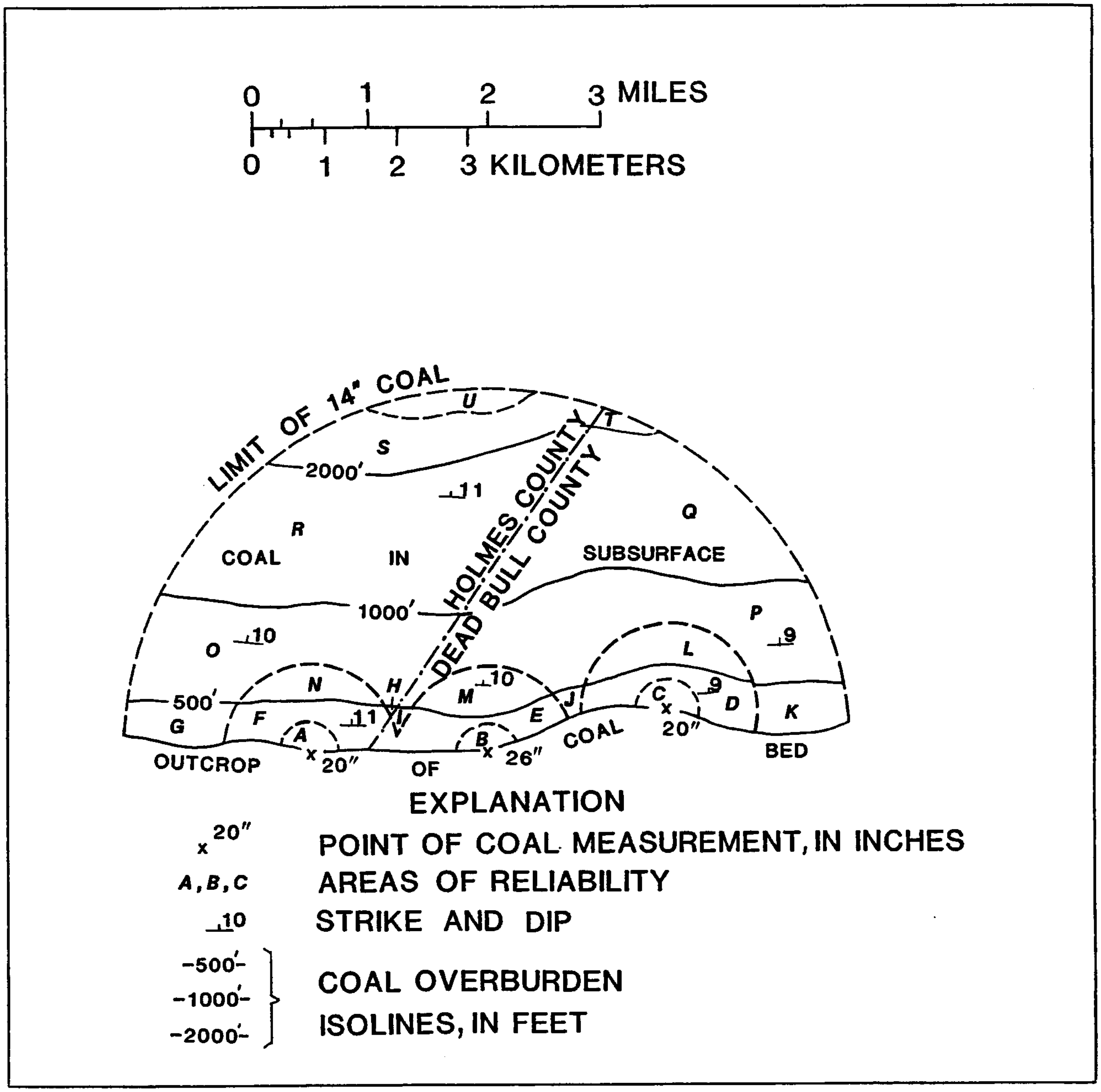

FIGURE 13.—Same basic diagram as figure 12. Shows determination of areas of reliability and 500–, 1,000– and 2,000–foot overburden contours which were obtained by subtracting elevations of bed from surface elevations. Bed elevations were obtained from a topographic map, from the outcrop of a coal bed, and from structure sections utilizing dips. Areas of reliability determined by using 1/4–mile radius (measured), 3/4–mile radius (indicated), 3–mile radius (inferred), and more-than-3-mile radius (hypothetical) from measurement points. Individual areas of reliability are identified by letters *A* through *U*.

national park, a national bird refuge, a State park, and a large lake, all of which merit assignment of the underlying coal in those areas to restricted categories.

Figure 22 demonstrates a small coal basin where many resource classification categories are distinguished, including two large areas of hypothetical coal. The figure also shows two coal beds that intertongue with an intervening linear sandstone body. The coal beds have been strip-mined at six localities and underground mined at three localities. The coal beds have been tested by 15 drill holes which revealed the existence of two coal beds separated by sandstone. Numerous surface measurements of coal thickness support the widespread extent of at least one bed, and three measurements revealed the relations of two coal beds with the sandstone body. A bed map of the basin revealed two

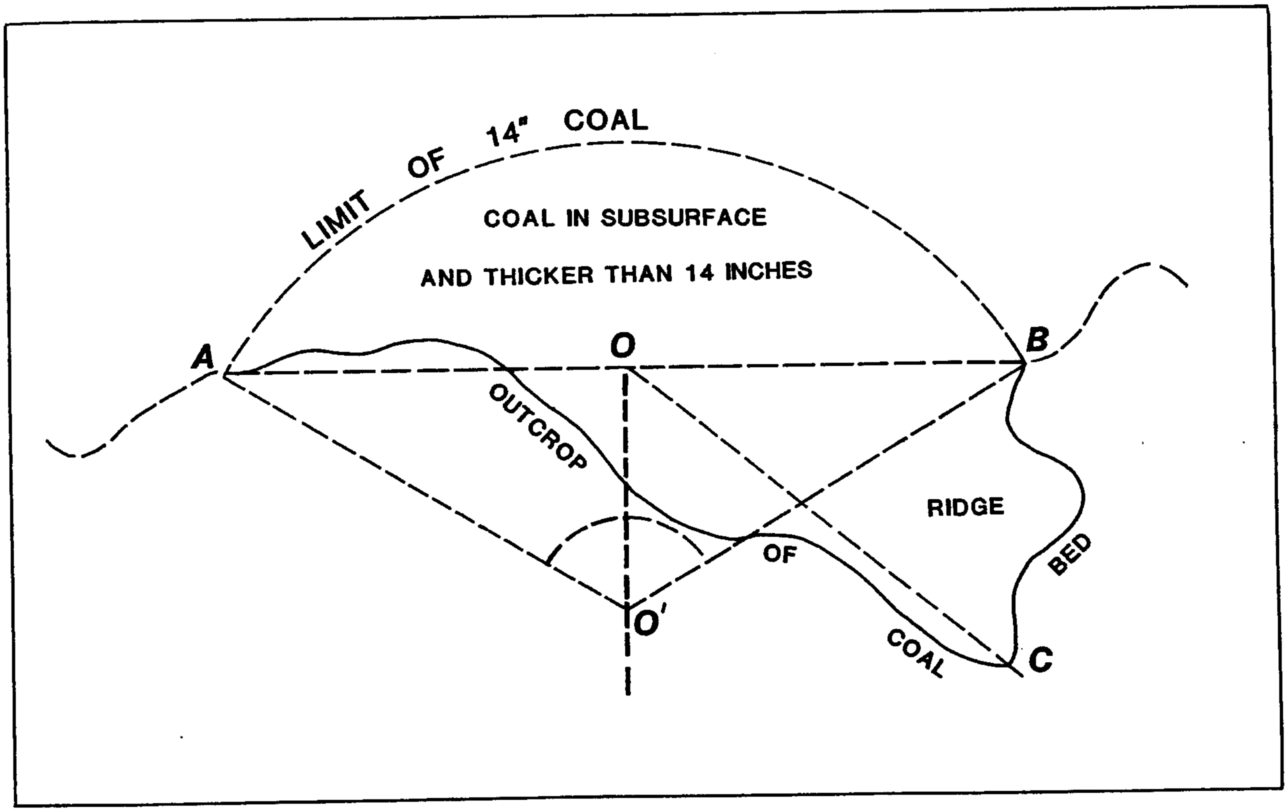

FIGURE 14.—A ridge showing construction of accepted 14-inch minimum thickness limit of a bituminous coal bed. Point *C* is the most distant point of outcrop on the ridge from end points *A* and *B*. Accepted 14-inch thickness of coal limit comprises an arc *AB*. Construction of arc *AB* is as follows: from midpoint *O* of line *AB*, draw line *OC* to furthest point on outcrop. Swing arcs from *A* and *B* with a radius of *OC*. The intersection of the arcs is point *O'*. From *O'* draw arc *AB* using either *AO'* or *BO'* as the radius.

TABLE 4.—*Areas of reliability from figure 13 listed by overburden and coal thickness categories, and by counties*

[Tonnage estimated for each area could be determined (1) by planimetering each area for acreage, and (2) by multiplying acreage by proper weight of coal per acre-inch by the average thickness of coal in the area. Average thickness of coal would be obtained by isopaching coal thickness as shown on figure 13]

Geologic assurance category	Coal thickness: 14 to 28 inches	Coal thickness: 28 to 42 inches
	0 to 500 feet overburden:	
Measured	*A, B, C*	None
Indicated	*D, E, F*	Do.
Inferred	*G, H, I, J, K*	Do.
	500 to 1,000 feet overburden:	
Indicated	*L, M, N*	None
Inferred	*O, P*	Do.
	1,000 to 2,000 feet overburden:	
Inferred	*Q, R*	None
	2,000 to 3,000 feet overburden:	
Inferred	*S, T*	None
Hypothetical	*U*	Do.

Political division: Holmes County	Political division: Dead Bull County
A, F, G, H, N, O, R, S, U	*B, C, D, E, I, J, K, L, M, P, Q, T*

coal-bearing areas separated stratigraphically and areally by an intervening sandstone body. The completed bed map in figure 22 allows the segregation and subsequent estimation of the resources of the two coal beds into a large number of categories enumerated in the caption for the figure. The two coal beds are subdivided by their heat values on a moist, mineral-matter-free basis into lignite and subbituminous coal. The 8,300-Btu isolines that represent the boundary between subbituminous coal and lignite are drawn so that tonnage estimates can be made for proper rank classification.

Figure 23 depicts a large but simple subbituminous coal and lignite basin that contains predominantly hypothetical resources traversed by three synclines and two anticlines. The total thickness of coal at each point of surface measurement and in each drill hole penetrating the coal zone is obtained by summing the thicknesses of all coal beds that are thick enough to be considered as resources (2.5 feet, or 75 cm). These thicknesses are isopached at 40-foot thick increments, and the overburden, heat value, and reliability categories are plotted

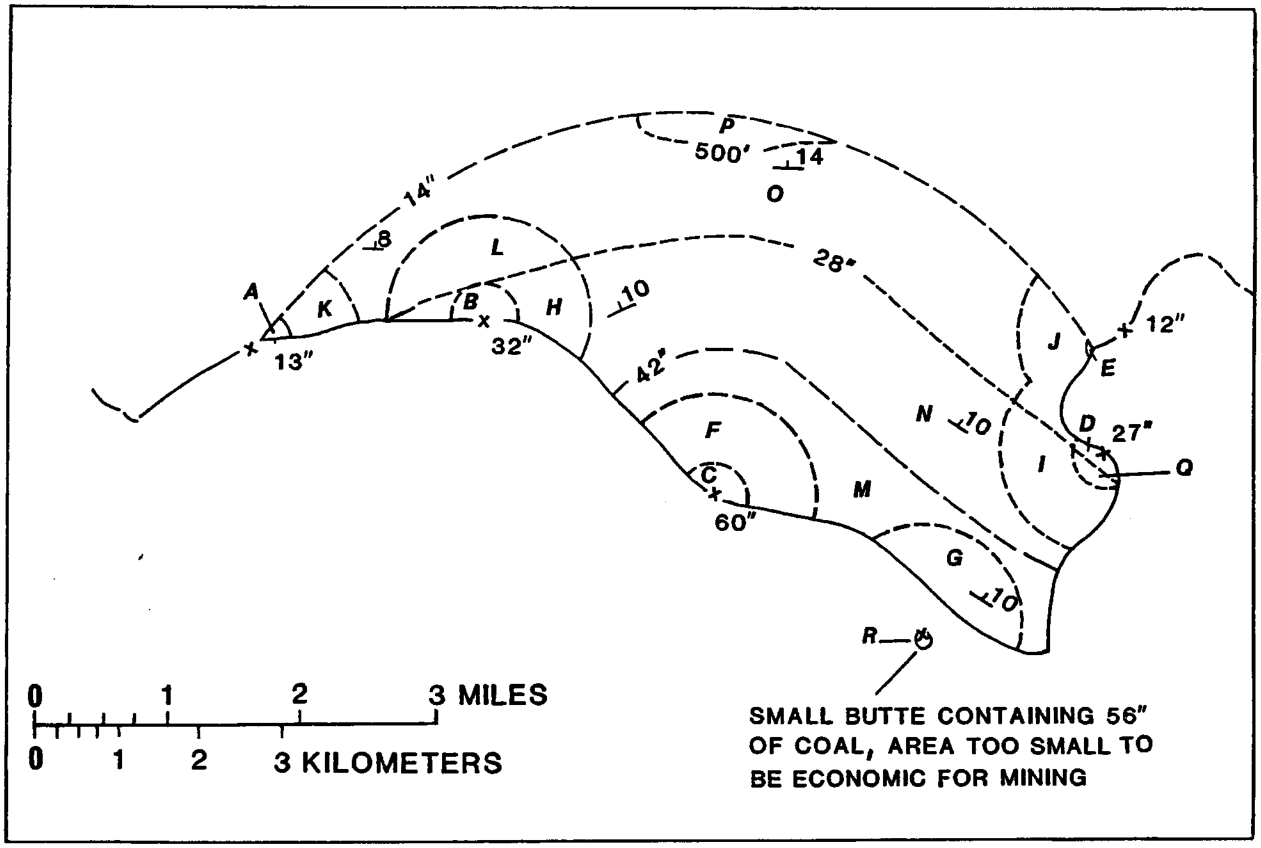

FIGURE 15.—Same ridge shown in figure 14 with the addition of an isolated butte containing bituminous coal. Shows determination of areas of reliability; 14–, 28–, and 42-inch coal isopachs, and 500-foot overburden contour. Categories defined by intersections of lines separating areas of reliability, thickness of coal, and thickness of overburden are labelled *A* through *R*. Overburden contour was computed from dips and by subtracting bed elevations from surface topographic elevations.

on the map. Estimates of coal tonnage should be calculated for each rank category. The total tonnage estimate for hypothetical resources in the example is the sum of each of these estimates. Generally, the size of the thickness of coal increments is left to the geologist to determine. Figure 23 is appropriate to an analysis based on a coal-zone approach to estimation of hypothetical resources as outlined on p. 37–38.

Figures 24 and 25 show suggested forms for recording coal resource data. These forms, or similar forms, are necessary for recording coal bed names; overburden and thickness of coal categories; planimeter readings; calculated areas; and weighted average thickness of coal for the area being calculated. The forms also provide columns for tabulating tonnage estimates in the measured, indicated, and inferred reliability categories, by coal thickness categories, and miscellaneous information such as planimeter factor, persons responsible for steps of work, and total tonnages by thickness and overburden categories. The data recorded on such forms and the calculations made therefrom represent the culmination of coal resource work starting in the field and continuing through the preparation of bed maps such as those in figures 9 through 23. The forms for data entry and calculation should be designed with care so the data entered on the forms from accompanying bed maps contain the necessary information for estimating all types of coal resources and reserves. This information can be combined with other information such as pertinent data on costs, transportation, and marketing to provide a documented analysis of the coal resources/reserves in a coal bed, field, region, basin, province, county, State, and (or) the Nation.

GEOPHYSICAL LOGS AS A SOURCE OF COAL BED DATA

Geophysical well logs have been invaluable in the search for oil and gas because they provide rapid, economical, and detailed information on the thickness, lithologic characteristics, fluid content, correlation,

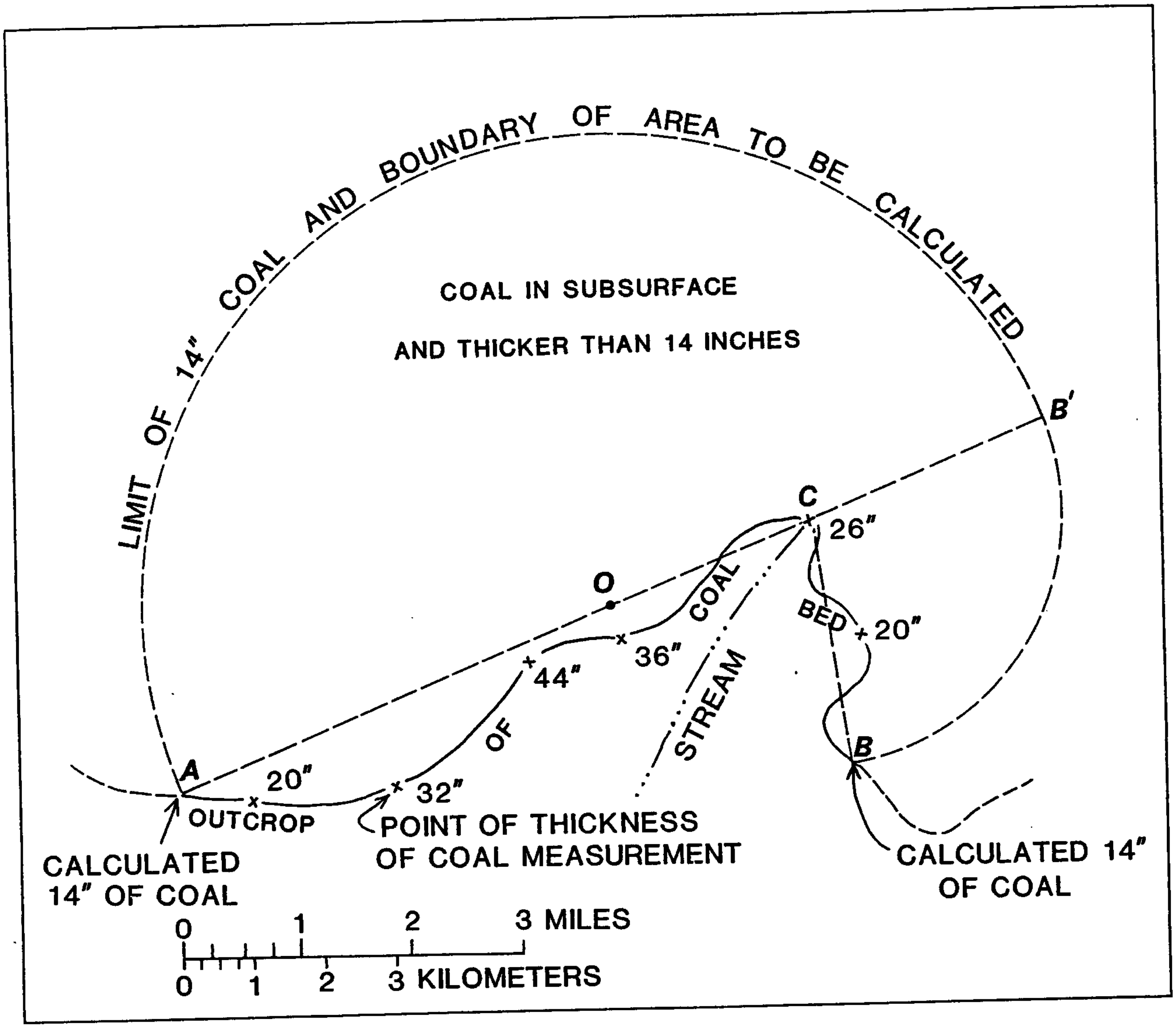

FIGURE 16.—A simple valley reentrant in a bituminous coal bed outcrop. Shows determination of 14-inch coal isopach and limit of area to be planimetered for underlying coal. The 14-inch coal thickness points were obtained by extrapolating data from points of measurement along outcrop line. Projected limits of coal resource isopach (14-inch coal) and area to be calculated are determined by constructing: (1) an arc *BB'* with origin at *C* drawn from *B* to the extension at *B'* of line *AC* and *CB*; and (2) final segment of arc *AB'* is drawn with origin at midpoint *O* of line *AB'*.

TABLE 5.—*Areas of reliability from figure 15 listed in proper overburden and coal thickness categories*

Geologic assurance category	Coal thickness: 14 to 28 inches	28 to 42 inches	42 to 84 inches
0 to 500 feet overburden:			
Measured	*A, D, E*	*B, Q*	*C, R*
Indicated	*J, K, L*	*I, H*	*G, D*
Inferred	*O*	*N*	*M*
500 to 1,000 feet overburden:			
Inferred	*P*	None	None

structure, and depth of strata penetrated by a well. Such logs have been run in many thousands of oil and gas exploratory, discovery, and producing wells that have penetrated coal-bearing strata in many regions of the country.

Geophysical logs can be used to identify coal beds and to quantify their resources because coal has several unique physical properties including low natural radioactivity, low density, and high resistance to electrical currents; these properties contrast with those of most

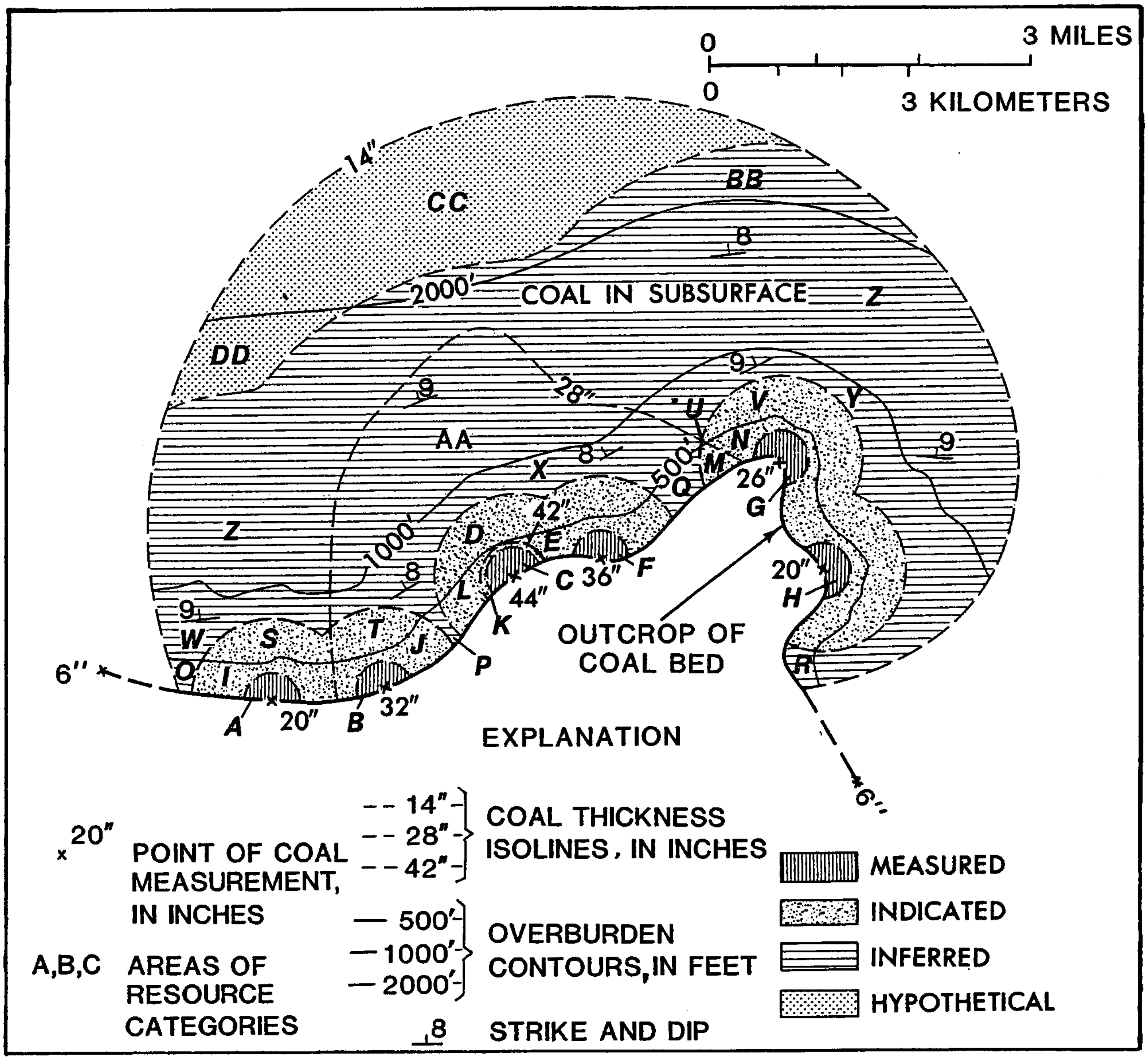

FIGURE 17.—Same diagram as figure 16. Shows determination of areas of reliability; 500-, 1,000-, and 2,000-foot overburden contours; and 14-inch, 28-inch, and 42-inch coal isopachs. Overburden contours were determined from surface elevations on a topographic map and by subtracting bed elevations utilizing structure sections, and dips. Coal isopachs were determined from points of coal thickness measurement and 14-inch limit of coal. Areas of reliability were determined by using 1/4-mile radius (measured), 3/4-mile radius (indicated), 3-mile radius (inferred), and more-than-3-mile radius (hypothetical) from points of thickness of coal measurement. Individual areas of resource categories are identified by letters *A* through *DD*.

other rocks in the coal-bearing sequence. Thus, geophysical logs can provide information on the existence, continuity, thickness, and correlation of shallow to deeply buried coal beds in known coal-bearing areas that have not yet been fully explored and in the future may provide information in areas not previously thought to contain coal. Most of these logs are available to the public through commercial companies and may be studied at State geological surveys or at similar agency offices in some States.

Caution should be used in evaluating and interpreting the existence, thickness, and correlation of coal beds from the geophysical logs of oil and gas exploratory and production wells for two reasons. First, if only one type of log is available, other rock types may be misidentified as coal, for example, highly resistive limestone on a resistivity log or pure quartz sandstone on a natural radioactivity log. However, this problem can be mitigated by a thorough knowledge of the coal-bearing strata in the area under investigation and by an under-

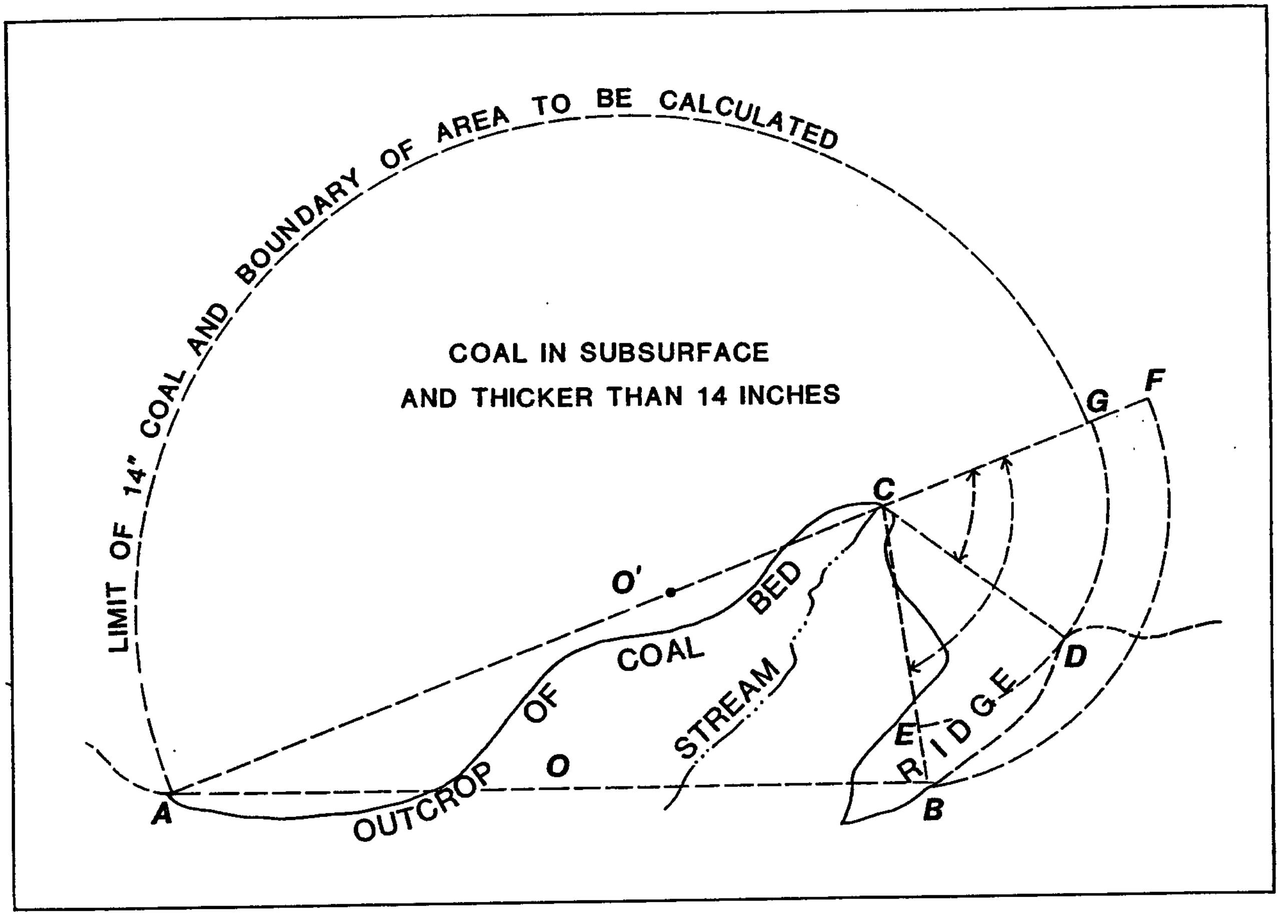

FIGURE 18.—A valley and ridge with part of coal bed less than minimum thickness but within determined 14-inch limit as illustrated in figure 16. Determined limit comprises the outcrop line from *A* to *B* and from *B* to *D* along the arc *B* through *D* to intersect projection of line *AC* at *G*. Radius *CD* is obtained from distance to nearest point of outcrop line, *D*, below minimum thickness. Arc *BF* using radius from line *BC* includes coal on outcrop line below minimum thickness and therefore is not acceptable. Arc *AG* is drawn from midpoint *O'* of line *AG*. Arc *EDG* is drawn from *C* to extend arc *AG*.

TABLE 6.—*Areas of resource categories from figure 17 listed in proper reliability and thickness of coal and overburden categories*

[Tonnage estimate for each area could be determined (1) by planimetering each area for acreage, and (2) by multiplying acreage by proper weight of coal per acre-inch by the average thickness of coal in the area. Thickness of coal for each area is obtained by referring to coal thickness isopachs]

Geologic assurance category	Coal thickness		
	14 to 28 inches	28 to 42 inches	42 to 84 inches
	0 to 500 feet overburden:		
Measured	*A, G, H*	*B, F*	*C*
Indicated	*I, N*	*E, J, L, M*	*K*
Inferred	*O, R*	*P, Q*	None
	500 to 1,000 feet overburden:		
Indicated	*S, V*	*T, D, U*	None
Inferred	*W, Y*	*X*	Do.
	1,000 to 2,000 feet overburden:		
Inferred	*Z*	*AA*	None
Hypothetical	*DD*	None	Do.
	2,000 to 3,000 feet overburden:		
Inferred	*BB*	None	None
Hypothetical	*CC*	do.	Do.

standing of how these strata are recorded on a log. For example, if limestone beds are not present in the coal-bearing sequence and if all sandstone beds are more radioactive than the coal beds, problems of lithologic identification are nonexistent. If several log types are available, the coal generally can be identified with confidence despite other strata with similar log characteristics in the sequence. Second, some oil and gas logs are not suitable for identifying coal beds for reasons that are not always clear because they give readings that either mask coal beds, indicate coal beds where none are present, or are ambiguous. Here again, a knowledge of the stratigraphic positions of coal beds in coal-bearing sequences will aid identificaiton of unsuitable logs. Because coal thicknesses interpreted from geophysical logs are considered as points of measurement for calculating coal resources, it is advisable to use only those coal thicknesses that are determined with confidence.

The geophysical log types generally used in coal bed recognition and stratigraphic identification and rank,

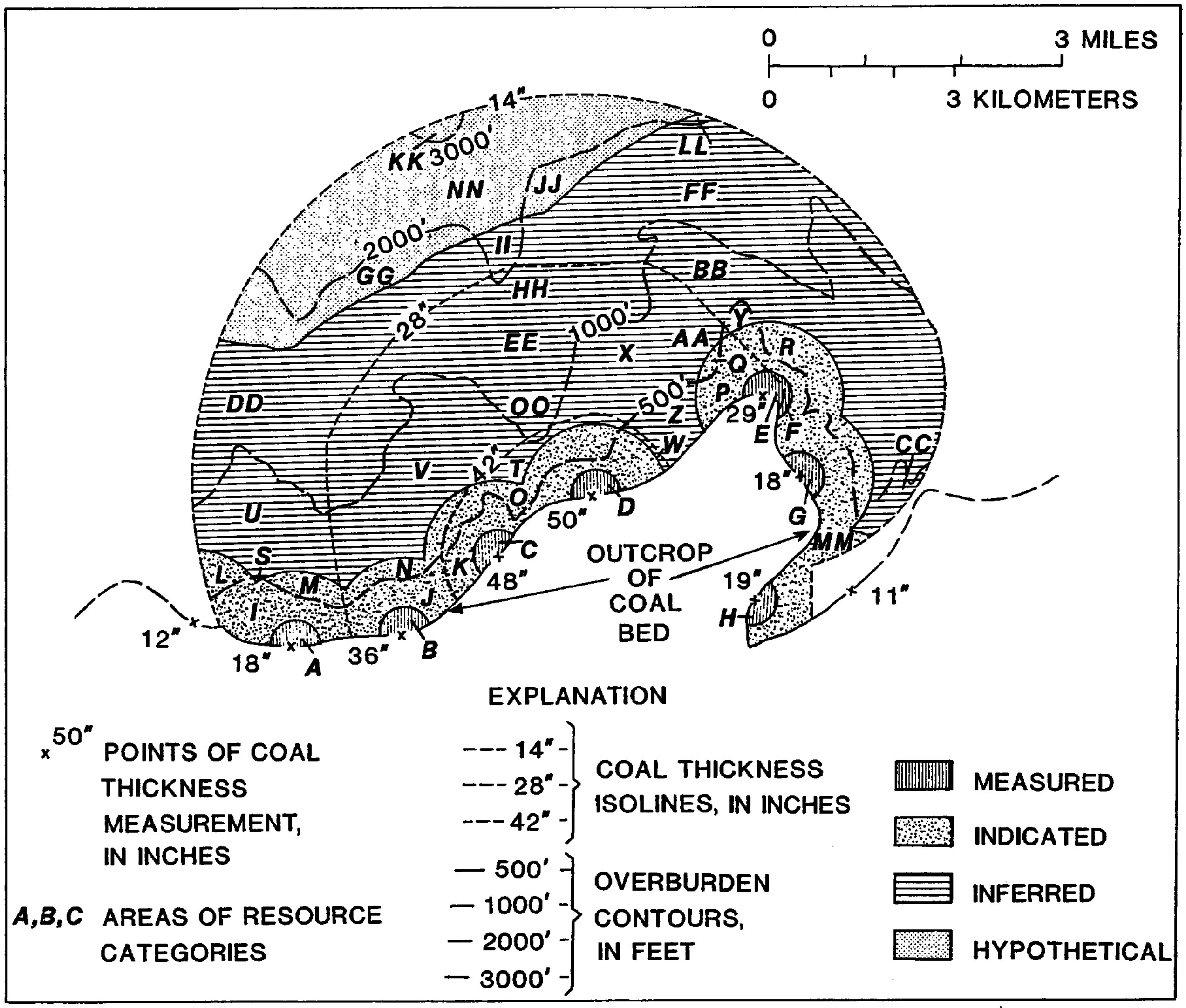

FIGURE 19.—Same diagram as figure 18. Shows determination of areas of reliability; 500-foot, 1,000-foot, 2,000-foot, and 3,000-foot overburden contours; and 14-inch, 28-inch, and 42-inch bituminous coal isopachs. Overburden contours are determined by subtracting bed elevations from surface topographic map elevations. Bed elevations are determined by utilizing structure sections and dips. Coal isopachs are obtained from points of coal thickness measurement and 14-inch limit of coal. Areas of reliability determined by using 1/4-mile radius (measured), 3/4-mile radius (indicated), 3-mile radius (inferred), and more-than-3-miles radius (hypothetical) from points of coal thickness measurement. Areas of resource categories are identified by letters *A* through *OO*.

quality, and thickness evaluations are the electrical, gamma ray, density, neutron, and acoustic velocity. The following discussion of log types is concerned principally with geophysical logs of oil and gas exploratory wells. It should be noted that coal exploration programs increasingly have become reliant on coal-oriented geophysical logs, which provide important data on thickness, depth, and correlation of coal beds, and locally on the composition of coal. A carefully chosen suite of coal-oriented logs can provide positive recognition of coal, identification of specific coal beds, and precise coal thickness measurements (Vaninetti and Thompson, 1982). Such suites are used currently to supplement information obtained from core holes, driller's logs, and examination of drill cuttings. They are useful especially where core or sample recovery of coal was incomplete. The ease and accuracy of recognizing, identifying, and evaluating coal beds with coal-oriented logs strongly contrasts with the difficulty of performing the same interpretations using the higher speed and less accurate geophysical logs of oil and gas wells, which generally are run at different instrument settings and with different equipment. Most oil and gas geophysical logs are recorded at a scale of 1 inch equals 50 feet, with selected

sections recorded at the larger scale of 1 inch equals 20 feet, which is reduced for commercial sale to 1 inch equals 100 feet and 1 inch equals 40 feet, respectively.

ELECTRIC LOGS

By far the most common geophysical logs run in oil and gas exploratory wells are electric logs. Prior to the 1950's, conventional electrical logging surveys consisted of one measurement of the spontaneous potential (SP) and three measurements of apparent electrical resistivity of the rocks adjacent to the bore hole (fig. 26). These rock properties were measured only in the uncased part of a well that was filled with water or a water-based mud. The diameter of the well and the effect of adjacent rocks combined to give confusing curves on older electric logs. In solving this problem, a new family of resistivity curves, the focusing-electrode and the induction logs, came into use in the late 1950's. These logs provide better resolution of the coal beds than the older conventional logs and permit more accurate coal thickness measurements.

SP LOG

The spontaneous potential (SP) log measures the difference in electrical potential between rock types, and the resulting curve is recorded on the left-hand side of the log as a single trace. This curve generally reflects the invasion of drilling fluid into the rocks, so a permeable sandstone bed tends to record as a large deflection to the left of the log response for shale (figs. 27 and 28). There are many exceptions to this generalization as shown by the deflections caused by high-porosity coal beds (see fig. 29, SP curve). There are also many wells where the SP curve is nearly featureless in a coal-bearing section and the porosity is recorded the same as shale (fig. 28*A* and *B*).

NORMAL AND LATERAL LOGS

Three types of resistivity curves are recorded on the right side of a geophysical log. These are the 16-inch normal (short normal); the 64-inch normal (long normal); and the 18-foot, 8-inch or 24-foot lateral (lateral); the names referring respectively to the spacing and to the configuration of the electrodes in the probe. These curves record the resistance of rock types to the flow of an electric current. Because most coal beds are highly

TABLE 7.—*Areas of resource categories from figure 19 listed in proper reliability and thickness of coal and overburden categories*

[Average thickness of coal in each area can be determined by utilizing coal isopachs]

Geologic assurance category	Coal thickness		
	14 to 28 inches	28 to 42 inches	42 to 84 inches
0 to 500 feet overburden:			
Measured	*A, F, G, H*	*B, E*	*C, D*
Indicated	*I, MM*	*I, J, P*	*K*
Inferred	*CC, Y, S*	*AA, Z*	*W*
500 to 1,000 feet overburden:			
Indicated	*L, R, M*	*N, Q*	*O*
Inferred	*U, BB*	*V, X*	*T*
1,000 to 2,000 feet overburden:			
Inferred	*DD, FF*	*EE*	None
Hypothetical	*GG, JJ*	None	Do.
2,000 to 3,000 feet overburden:			
Inferred	*LL, II*	*HH*	*OO*
Hypothetical	*NN*	None	None
3,000 to 6,000 feet overburden:			
Hypothetical	*KK*	None	None

resistant to the flow of an electric current compared with most adjacent rocks, resistivity curves generally show a large deflection opposite a coal bed. In the short and long (16-inch and 64-inch, respectively) normal curves, however, coal beds thinner than the electrode spacing show a "reverse" (low resistivity) curve bounded by two small peaks (fig. 28*A* and *B*, No. 6 coal). The lateral curve shows a large deflection opposite thin coal beds and a low deflection below the bed. The lateral curve is of little value in the measurement of the thickness of coal beds because it is asymmetric and generally offset from the coal bed. Nevertheless, this curve can be useful in correlating coal beds (fig. 28*A* and *B*).

FOCUSING-ELECTRODE AND INDUCTION LOGS

Focusing-electrode logs (for example, lateral logs) use special electrodes to send a narrow focused electric current horizontally into adjacent rocks. This results in a resistivity curve that has good resolution of thin resistive beds such as coal (figs. 29 and 30). These focusing and lateral logs measure the conductivity (inverse of resistivity) and the resistivity of rocks by means of induced alternating currents. Commonly, an induction log is run in conjunction with a SP and 16-inch normal log (fig. 27). The induction log is recorded simultaneously as two curves, conductivity and resistivity. The conductivity curve is hyperbolic, which compresses the parts of the curve characterized by low conductivity.

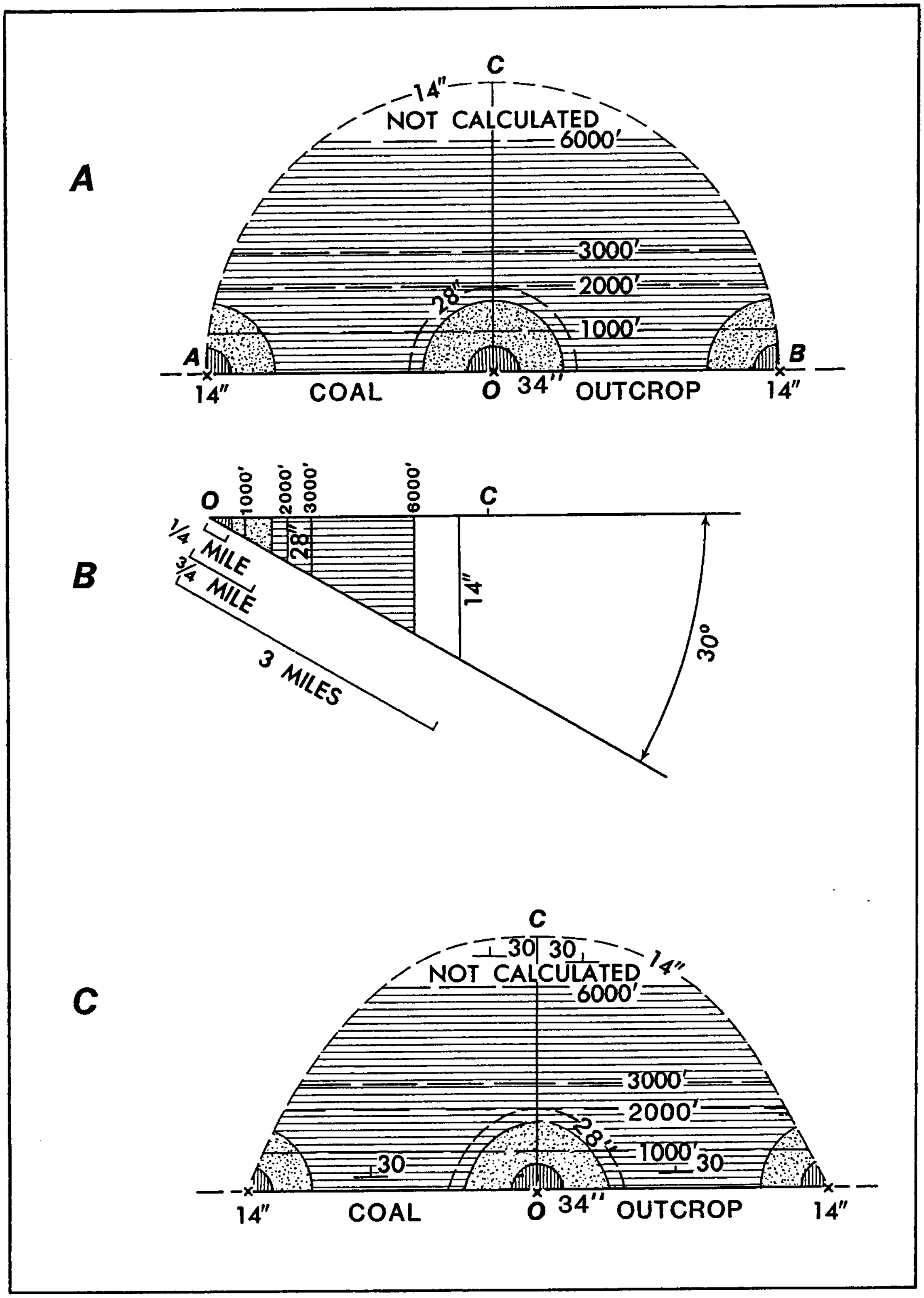

FIGURE 20.—Diagrams showing *A*, Coal categories in plane of coal bed. *B*, Structure section *OC* showing relations between features measured in plane of bed and ground surface when bed dips 30°. *C*, Coal categories as viewed projected to the ground surface from plane of coal bed. Note contraction of category areas towards the outcrop as compared to plane of coal bed; contraction is due to dip.

The resistivity curve, however, is not compressed, so it can be compared directly to the short normal curve and can be used for measurement of the thickness of a coal bed. Combinations of induction and focusing-electrode logs are also common.

DISCUSSION OF ELECTRIC LOGS

With the exception of some high-moisture-content lignites, most coal beds are responsible for high-resistivity deflections on resistivity curves. However, some other rock types such as limestone or resistive sandstones also show high-resistivity deflections and may be mistaken for coal. Limestone is indistinguishable from coal on most electric logs. Fortunately, limestone beds are absent in many regions. In the Midcontinent region, however, limestone is abundant in the coal-bearing sequence and generally can be differentiated from coal only by use of supplementary logs (see fig. 31) or by examination of closely spaced samples of drill cuttings.

Resistive sandstone beds that are permeable generally can be differentiated from coal beds because of their large deflections on a SP log (figs. 26, 27, and 28). Where a SP log is featureless or ambiguous, a knowledge of the lithology of a coal-bearing sequence can help differentiate coal from sandstone. For example, in the Powder River basin of Montana and Wyoming, many sandstone beds are gradational with adjacent low resistivity shale beds, whereas the shale beds are in sharp contrast with adjacent high-resistivity coal beds. As a result, the resistivity curves delineating coal beds are more nearly parallel than the curves representing the contacts of sandstone beds.

GAMMA RAY LOG

The gamma ray log records the natural gamma radiation from rocks adjacent to a drill hole. Coal generally has low natural radioactivity as compared with other rocks, particularly shale, in a coal-bearing sequence (figs. 29, 30, and 31). In some coal-bearing regions, limestone and sandstone may have similar low natural radioactivity (for example, Midcontinent or Appalachian regions) so that in those regions supplemental logs such as density or acoustic velocity are needed to identify coal. In other regions, gamma ray logs alone are sufficient to identify coal beds as, for example, in the Fruitland Formation (Fassett and Hinds, 1971) and in the Northern Great Plains where no other rock types in the Tertiary coal-bearing sequence, including limestone, are known to have as low a natural radioactivity as coal. Even in areas where a gamma ray log is diagnostic of coal, a few oil and gas well gamma ray logs are useless because their time constant is so long and their sensitivity is so low that a coal bed either cannot be detected or its boundaries are obscured. Locally some coal beds are uraniferous; consequently, a high radioactivity is recorded on gamma ray logs. These uranium-bearing coal beds usually can be identified by using other logging methods.

A gamma ray log is the most versatile of the geophysical logs for the following reasons: (1) it does not require fluid in the hole; (2) it is not sensitive to small variations in hole diameter; and (3) it can be used to detect coal beds through well casing. In fact, near-surface gamma ray logs of cased oil and gas wells are a prime source of data for identifying and measuring the thickness of shallow coal beds in the Northern Great Plains region.

The gamma ray logs can detect shale partings in a coal bed, but generally the thickness of thin partings is exaggerated. In the Powder River basin of Montana, there is an example where the gamma ray log records a 0.3-foot shale parting at the same thickness as a 2-foot parting.

DENSITY LOG

A gamma-gamma density log records the bulk density of rocks adjacent to a drill hole by measuring the induced gamma rays emitted by the rocks after bombardment by a gamma ray source encased in a probe and lowered into the drill hole. The denser the adjacent rocks, the more gamma rays are absorbed and not returned to a detector in the probe where they are measured in grams/cm^3. Most ranks of coal are low in density (about 0.7 to 1.8 grams/cm^3) compared to adjacent rocks; therefore, a density log is an excellent tool for coal-bed evaluation. The density log is capable of identifying detailed variations in the density of rocks. Density logs from oil and gas wells are commonly run at 30 feet per minute, are recorded at 1 inch equals 20 feet, and then are reduced to 1 inch equals 100 feet. At this scale and speed, thin coal beds and partings can be detected and their thicknesses accurately measured (fig. 30). Unfortunately, density logs must be run in uncased holes and are strongly affected by differences in hole diameter; thus, the curve recorded for a caved or enlarged part of a well may simulate the curve of a coal bed. A caliper log, which measures the diameter of a well, is generally run in conjunction with these logs so that the proper interpretation and correction can be made.